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Interactive comment on "Global soil organic carbon removal by water erosion under climate change and land use change during 1850–2005 AD" *by* Victoria Naipal et al.

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We would like to thank the anonymous reviewer for his or her constructive comments. In this response we provide an answer to all the comments and the indicated changes will be applied in the revised manuscript.

Comment 1: "The emulator used in this study seems to have various limitations that make the numbers presented quite uncertain – further discussion on, and quantification of, these uncertainties is warranted and would greatly improve this manuscript. Specifically, I would have liked to see additional support for the SOC model formulation, parameters, and built-in feedbacks chosen for the emulator, as well as support

for its vertical discretization and parameterization. The carbon emulator is supposed to describe the carbon pools and fluxes exactly as in ORCHIDEE, yet the total global SOC stocks from the emulator are 44% higher than that of the original ORCHIDEE model. This is a big difference. What does this tell us about the accuracy and applicability of the emulator, and how do the SOC stocks of the two models compare to the Harmonized World Soil Database (HWSD) and other global SOC databases? Additional major comments/questions, especially those regarding the assumptions and methods used, are detailed below.

Answer: We modified the vertical discretization scheme of the emulator in such a way that the total SOC stock of each grid cell, PFT and C pool is close to that of ORCHIDEE when soil erosion and land use change is deactivated (0.5% max difference in total global SOC stock). For this we calibrated both the exponent 're' and variable 'k0i' of equation 5 in the manuscript for each grid cell and PFT under equilibrium conditions, such that the total soil respiration per grid cell, PFT, and soil C pool of the emulator would be similar to that of the ORCHIDEE model. For the transient period (1850-2005), we made 're' remain equal to the equilibrium state values, while values for 'ki0' were derived at a daily time-step to keep to SOC stocks of the emulator similar to those of ORCHIDEE and preserve the yearly variability in the soil respiration rates due to changes in soil climate (soil erosion and land use change were deactivated). Details of how we calibrated the exponent 're' and variable 'k0i' we describe in our response to Reviewer 1. The modified vertical discretization scheme did change the values of the SOC stocks and SOC removal rates, because with this scheme we simulated total SOC such as in the ORCHIDEE model without soil erosion and land use change. However, the overall trends in soil and SOC erosion rates and cumulative changes in SOC stocks during the transient period did not change significantly and the main findings of our study remain unchanged. For more details on the changes in our manuscript related to the modified vertical discretization scheme see our detailed response to reviewer 1.

We performed a comparison of our simulated SOC stocks to the Global Soil Database for Earth System Modeling (GSDE), as is described in paragraph 3.2 and the new table 5 of the manuscript (with results based on the new vertical discretization scheme). However, we abstained from a more in-depth comparison as our emulator and ORCHIDEE do not include various soil processes that have been proven to affect SOC substantially such as vertical mixing, diffusion, priming, changes in soil texture, C rich organic soils formation, etc.

It should be noted that there are also large uncertainties in the global soil databases (Hengl et al., 2014; Scharlemann et al., 2014; Tifafi et al., 2018), which makes the exact quantification of the uncertainties of the resulting SOC dynamics simulated by our emulator difficult. After applying the modifications to the vertical SOC discretization scheme, we performed a simulation with soil erosion and land use change activated (S1) and compared the resulting SOC stocks with those from the GSDE. Figure S1 shows that our emulator, and the ORCHIDEE model in general, underestimates SOC stocks globally, except for the high-latitudes.

Changes in manuscript: We will put figure S1 in the supporting material. Furthermore, the values of table 5 of the manuscript are modified and the new table that will be included in the manuscript is presented in the supplement. L394:" We abstained from a more in-depth comparison as our emulator and ORCHIDEE do not include various soil processes that have been proven to affect SOC substantially such as vertical mixing, diffusion, priming, changes in soil texture, C rich organic soils formation, etc. It should be noted that there are also large uncertainties in the global soil databases (Hengl et al., 2014; Scharlemann et al., 2014; Tifafi et al., 2018), which makes the exact quantification of the uncertainties of the resulting SOC dynamics simulated by our emulator difficult."

Answer: Some of these processes are already included in the ORCHIDEE model, which is the basis for the C emulator but other feedbacks on SOC are missing in the original ORCHIDEE model such as the effect of SOC on the hydrology or on the thermic of the model. Nevertheless, our main objective here was to present a tool able to

evaluate erosion fluxes at global scale using a 'state-of-art' land surface model outputs and estimate the drivers of erosion at global scale. In addition, this study did not focus on the feedbacks of soil erosion and land use change on NPP, the hydrological cycle or nutrient cycle and therefore it was decided not to incorporate soil erosion processes directly into ORCHIDEE, but rather use the C emulator concept instead. Not including these processes explicitly in the emulator does not change the simulated SOC dynamics in our study. However, the emulator has a flexible structure and could be made more complex depending on the needs, such as including a more sophisticated vertical discretization scheme. The main idea of the emulator was to use a modeling tool that does not require much computational power but that still incorporates the basic processes and variables for simulating large-scale SOC dynamics under soil erosion and land use change. Many simulations were needed to quantify the various effects of soil erosion on the C cycle and to calibrate the model parameters. The C emulator was in this case a convenient tool, as it is fast and its structure allows to easy switch processes on or off.

Changes in manuscript: In chapter 2.1 we will rewrite the text between the lines 131 and 136 as following: "…in the emulator. Some of these processes are already included in the ORCHIDEE model, which is the basis for the C emulator. In addition, this study did not focus on the feedbacks of soil erosion and land use change on NPP, the hydrological cycle or nutrient cycle and therefore it was decided not to incorporate soil erosion processes directly into ORCHIDEE, but rather use the C emulator concept instead. Not including these processes explicitly in the emulator does not change the simulated SOC dynamics in our study. The emulator preserves the structure of the carbon cycle of ORCHIDEE and is able to reproduce the outputs exactly as by the full ORCHIDEE model (Fig 1A). At face value, the emulator merely copies the ORCHIDEE carbon pool dynamics, and for each new atmospheric CO2- and climate scenario a new run of the original LSM is required. Our main objective here was to present a tool able to evaluate erosion fluxes at global scale using a 'state-of-art' land surface model outputs and estimate the drivers of erosion at global scale."

Specific comment 2: “L141-142: although originally calculated by complex equations, the dynamic evolution of each pool can be described using the first-order model" – why were the complex equations needed initially then? Again, what are the limitations of this first-order model?

Answer: The limitations of this first-order model are the incapability to capture feedbacks on the hydrological processes or on the NPP (see answer to previous comment). However, because the SOC is represented by first order equations inside ORCHIDEE and the complex equations only compute the modifier to the default coefficients, and as our study focused on the effects of soil erosion on the SOC dynamics, we decided to use the C emulator, assuming that erosion will not significantly impact soil physics (and in turn decomposition) affecting SOC. The complex equations, such as photosynthesis and hydrological processes are needed to simulate realistically the changes in biomass, litter and soil respiration over time, which is done by ORCHIDEE. In the original ORCHIDEE simulations, these processes are explicitly simulated on a 30 min time step. Such a time step is needed for coupled simulations with a climate model, but makes the model CPU intensive, and there is no need for such high-resolution calculations of ‘fast’ C fluxes for erosion induced effects on SOC. In the emulator, all C fluxes between ecosystem compartments (with and without erosion) are exactly the same as the original ORCHIDEE, assuming that there is no feedbacks between erosion and these fluxes. The C emulator is much more computational efficient than the original ORCHIDEE because it does not require to compute all ‘fast’ processes for all simulations. The emulator thus allows us to conduct a lot of simulations (e.g. with and without climate change, with and without CO2 fertilization, with and without land use change, with and without erosion), and at the same time keep the main features (except erosion) of the original ORCHIDEE simulation.

Changes in manuscript: L143:”. . .Eq.1. The complex equations, such as photosynthesis and hydrological processes are needed to simulate realistically the changes in biomass, litter and soil respiration over time, which is done by ORCHIDEE. In the original ORCHIDEE simulations, these processes are explicitly simulated on a 30 min time step. Such a time step is needed for coupled simulations with a climate model, but makes the model CPU intensive, and there is no need for such high-resolution calculations of ‘fast’ C fluxes for erosion induced effects on SOC. In the emulator, all C fluxes between ecosystem compartments (with and without erosion) are exactly the same as the original ORCHIDEE, assuming that there is no feedbacks between erosion and these fluxes. Based on the output stock and fluxes of the original ORCHIDEE model, the values of the turnover rates are calculated and archived together with the input fluxes. They are then used. . .”

âĂČ Specific comment 3: “L180: What does the passive pool correspond to (as a measureable pool)? Why is there no transfer from p to s (k_ps)? Why no input to this pool?”

Answer: The distribution of SOC into an active, slow and passive pool and the transfer rates between these pools are based on the work of Parton et al. (1988). These pools are defined by their different residence times. The active, slow and passive SOC pools have a residence time of 1.5, 25 and 1000 years, respectively. That study defines the passive pool as a pool that is very resistant to decomposition and includes physically and chemically stabilized SOM. The proportions of the decomposition products which enter the passive pool from the slow and active pools increase with increasing soil clay content. Passive C is thus not directly produced from litter input but active or slow C has to be stabilized first to become passive C. Then, the original model of Parton et al., (1988) assumes that when the passive pool is decomposed by microorganisms, they produce metabolites corresponding to more labile materials that are released in the soil solution during microbial death and the associated cell lysis. For these reasons, they considered that the decomposed passive pool can only by recycled into the active pool.

Changes in manuscript: L181: “The SOC pools are based on the study of Parton et al. (1988) and are defined by their residence times. The active SOC pool has the lowest residence time (~1.5 years) and the passive the highest (1000 years).”

Specific comment 4: “L190: Does this allow for emergent differences in the relative distribution of the three pools with depth? (e.g., relatively more passive C than active C with depth, etc.)

Answer: Yes, the old vertical discretization scheme allowed for different relative distributions of the three pools with depth. However, we changed this aspect by assuming that the ratios between the three pools do not change with depth as we have no data on how these ratios should change (see reply to rev #1). In addition, we do not simulate the underlying processes that would allow for changing ratios between the SOC pools such as changing clay content with depth, diffusion, bioturbation.

Specific comment 5: “L196: "The SOC respiration rates for the topsoil layers are equal to those from ORCHIDEE". But how about subsoil respiration? Does the emulator have more respiration overall then? Please clarify how the models compare.”

Answer: We modified the vertical discretization scheme, so that the emulator now has a similar SOC respiration rate as ORCHIDEE without soil erosion or land use change. See our response to the first comment and to the comments of reviewer 1.

Specific comment 6: “L207-208: "total global SOC stock is approximately 44% larger than that from the original ORCHIDEE model" – what does this tell us about the accuracy and applicability of the emulator? This seems to be a big difference. How do the SOC stocks of the two compare to the HWSD and other global SOC databases?”

Answer: We modified the vertical discretization scheme, where the emulator has similar SOC stocks as ORCHIDEE without soil erosion or land use change. For more details see our response to the first comment of reviewer 1.

Specific comment 7: “L209-210: How are these fractions determined? What are the implications of the uncertainty in this partitioning?”

Answer: Above and below-ground litter consists out of plant residues and organic animal excreta that are partitioned into structural and metabolic pools as a function of the lignin to N ratio in the residue (Parton et al., 1988). The lignin and N ratios are usually prescribed per PFT and derived from plant-trait databases. This partitioning is prescribed by Parton et al. (1988) and followed by Krinner et al. (2005). The structural litter pool has a slower decay rate and contains the more recalcitrant molecules, while the metabolic pool has a faster decay rate and contains labile plant material. The decay rates are a function of temperature and humidity (Krinner et al., 2005). The lignin fraction of the plant material does not go through the active pool but is assumed to go directly to the slow C pool as the structural plant material decomposes. This is why part of the decomposed structural litter pool goes the active SOC pool and another to the slow SOC pool. Metabolic litter can be decomposed into active SOC and could also form a mineral-stabilized SOC (slow SOC pool, Cotrufo et al., 2015). The CENTURY model simulates the dynamics of C and nutrients (Parton et al., 1988), and is widely applied and tested in Land Surface Models. There are definitely large uncertainties in the partitioning of the litter pools, however, it is not in the scope of this paper to discuss these uncertainties.

Changes in manuscript: L211: “These litter fractions are based on the Century model as introduced by Parton et al.(1988) and later implemented inside ORCHIDEE (Krinner et al., 2005)..”

Specific comment 8: “L269: Why "randomly projected"? Please explain how and why.”

Answer: “Randomly projected”, means that the climate of the years after 1900 was randomly assigned to the years between 1850 and 1900 because the climate data of CRU-NCEP was only available starting from year 1900. If we would choose to repeat for example the climates of 1900-1910, we would risk including the effects of extreme climate conditions multiple times, which is not the case when a random projection is used. Changes in the manuscript: After line 270 we will add: “This is done because the climate data of CRU-NCEP was only available starting from year 1900, and to avoid the risk of including the effects of extreme climate conditions multiple times if only a certain decade would be used repeatedly."

Specific comment 9: "L290: But you used CRU-NCEP for ORCHIDEE... what are the caveats of using different climate datasets for each model?"

Answer: We compared the historical trend in yearly total precipitation between CRU-NCEP and ISIMIP2b, see figure S2. We find that although the ISIMIP2b shows a higher overall precipitation amount, the temporal trend and variability are similar to that of CRU-NCEP. If we would use CRU-NCEP to calculate the soil erosion rates, we expect that the new soil erosion rates would fall inside the uncertainty range created by calculation of the R- and the C-factors of the Adj. RUSLE (see answer to the last comment).

Specific comment 10: "L297: Why this dataset? How does it compare to the HWSD and SoilGrids (Hengl et al. PLoS ONE 2014, 2017) datasets?"

Answer: The GSDE is based on the SoilMap of the World (FAO, 1995, 2003) and various regional and national soil databases. It is available at a 1km resolution and at 5 arcmin resolution and contains updated soil information and more soil variables such as nutrients. The GSDE is based on more regional soil maps and is more up to date on soil information than the HWSD but both products compared relatively well since they shared several data (Shangguan et al., 2014). We did not test the SoilGrids data, which is based on a different approach. A recent publication showed that SoilGrids give different results compared to HWSD (Tifafi et al., 2018) but regarding the difference between the products we decided to use only one of them already used to evaluate erosion process and then be more comparable with previous publications (Naipal et al., 2015, 2016).

Specific comment 11: L342: How uncertain are these numbers given the model formulation assumptions, land-use maps, and methods used? It would help to see a sensitivity analysis and some uncertainty ranges.

Answer: We performed 4 additional simulations with a different PFT map, which is also based on the LUH2 land use dataset but where the historical forest area change that is not constrained by data as done by Peng et al. (2017). We used these simulations to show the differences to our results when other land use maps are used. If the forest is not constrained with methods described by Peng et al. (2017), there is a stronger decrease in forest area over the period 1850-2005. Also the grassland shows an increasing trend, while in the PFT map with constrained forest the grassland shows globally a slight decreasing trend. In the rest of the text we will refer to the PFT map constrained with data on forest area as the 'constrained PFT map' and to the other PFT map as the 'unconstrained PFT map'. Differences in global average soil erosion rates between the different PFT maps are small, however, there are significant differences in the SOC erosion rates and cumulative changes in SOC stocks during the transient period. According to the unconstrained PFT map, soil erosion leads to a total SOC removal of 79 Pg (simulation S1 with the new vertical discretization scheme) over the period 1850-2005, which is 6Pg larger than the total SOC removal by soil erosion under the constrained PFT map. Interestingly, according to the unconstrained PFT map, the global cumulative SOC stock change over 1850-2005 under soil erosion and LUC (S1) is 60% smaller than the stock derived using the constrained PFT map. This is most likely due to the higher forest area at the start of the period A850-2005, leading to a larger increase in SOC stocks by increasing atmospheric CO2 concentrations. The global LUC effect on the SOC stocks of both PFT maps is found to be similar. For more details and our changes in the manuscript see our answer to comment 2 of reviewer 1.

Specific comment 12: "L517: (Section 4.4) with all of these model limitations, it would be nice to have a rough quantification of uncertainties."

Answer: We agree with the reviewer that quantifying the uncertainty is important. Therefore, we derived an uncertainty range for our soil erosion rates. First, we varied the R-factor of the Adj.RUSLE model between a maximum and a minimum based on the regression equations derived by Naipal et al. (2015) per climate zone. Then we varied the C-factor of the Adj.RUSLE model between a maximum and minimum value per land cover type (tree, crop or grass) based on literature. We then used the uncertainty range in the C and R factors to derive the uncertainty range in the soil erosion rates and subsequently in the SOC erosion rates. We performed 4 additional simulations with the emulator, 2 simulations with the setup of S1 and a minimum and maximum soil erosion scenario, and 2 simulations with the setup of S2 with a maximum and minimum soil erosion scenario. The changes in our manuscript due to these uncertainty ranges and the new vertical discretization scheme are described below.

Changes in the manuscript: We make the following changes to the abstract: L26: “We found that over the period 1850-2005 AD acceleration of soil erosion leads to a total potential SOC removal flux of 73±17 Pg C of which 80-97% occurs on agricultural, pasture and natural grass lands” L28: “Including soil erosion in the SOC-dynamics scheme results in an increase of 54-70% of the cumulative loss of SOC. . .” L30:” This additional erosional loss decreases the cumulative global carbon sink on land by about 2 Pg for this specific period,. . .”

We make the following changes in the results chapter: L341-346:” After including soil erosion in the ORCHIDEE emulator we obtain a total global soil loss flux of 47.6±10 Pg y-1 for the year 2005 of which about 20-29% is attributed to agricultural land and 51-55% to grassland (natural grass and pasture). This global soil loss flux (here ‘loss’ meaning horizontal removal by erosion) leads to a total SOC loss flux of 0.52±0.14 Pg C y-1 of which about 26-33% are attributed to agricultural land and 54-64% to grassland (CTR, Fig 4).” L347:” The total soil and SOC losses in the year 2005 are an increase of 11-19% and 23-35%, respectively,. . .” L355-358:” We found that the total soil erosion flux on agricultural land increased with 55-60% by the year 2005 compared to 1850, while the SOC erosion flux increased by 11-70% (Fig. 4) and led to a cumulative SOC removal of 22±5 Pg on agricultural land since 1850 (CTR). On pasture land and grassland, the soil erosion flux increased by only 8-20%, while the SOC erosion flux increased by 44-54% (Fig. 4) and led to a cumulative SOC mobilization of 38±7

Pg since 1850.” It is evident that on agricultural land the uncertainty range in soil erosion leads to a large uncertainty range in SOC erosion compared to grassland. The increase in SOC erosion is much larger than the increase in soil erosion on grasslands because in our model, LUC (without erosion) leads to a significant increase in SOC on grassland, which amplifies the increasing trend in SOC erosion for grassland. This simulated increase for SOC stocks on grasslands. . .” L364-365: “In total 7183±1662 Pg of soil and 73±17 Pg of SOC is mobilized across all PFTs by erosion during the period 1850 - 2005, which is equal to approximately 46-74% of the total net flux of carbon lost as CO2 to the atmosphere due to LUC . . .” L395-397: “Using the Adj.RUSLE model to estimate agricultural soil loss by water erosion for the year 2005 resulted in a global soil loss flux of 12.28±4.62 Pg y-1 (Fig. 4). This flux is paralleled by a SOC loss flux of 0.16±0.06 Pg C y-1 after including soil erosion in the CTR simulation (Fig. 4). “ L405-406: “Furthermore, we find a cumulative soil loss of 1888±753 Pg and cumulative SOC removal flux of 22±5 Pg from agricultural land over the entire time period (CTR simulation).”

We make the following changes in the discussion chapter: L473-474:” . . .absence of erosion (S3-S4) by 4±2 Pg or a factor of 1.1-1.4 (Fig. 6A). This leads to a total change in the overall carbon stock on land of -105±2 Pg.” L493:” . . .and leads even to a net cumulative sink of carbon on land over this period of about 30±2 Pg C (S3).”

We make the following changes to the conclusion chapter: L551: “This potential soil loss flux mobilized 73±17 Pg of SOC across all PFTs, which compares to 46-74% of the total net flux of carbon lost as CO2” L553:” When assuming that all this SOC mobilized is respired we find that the overall SOC change over the period 1850-2005 would increase by 54-70%.”

The new tables with uncertainty ranges are provided in the supplementary material.

Please also note the supplement to this comment:
https://www.biogeosciences-discuss.net/bg-2017-527/bg-2017-527-AC2-

supplement.pdf

Interactive comment on Biogeosciences Discuss., https://doi.org/10.5194/bg-2017-527, 2018.

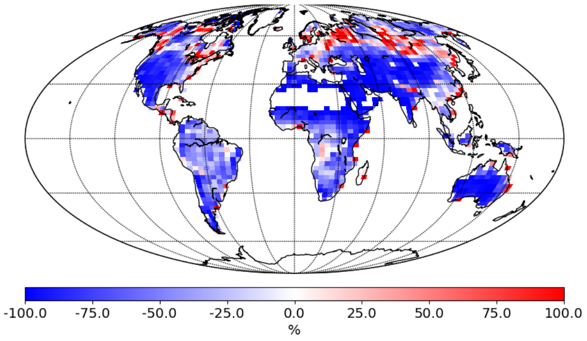

Figure S1: Difference between SOC stocks of the emulator (simulation S1) and the SOC stocks of GSDE as a percentage of the SOC stocks of GSDE till 2m depth. Red colors show larger SOC stocks by the emulator, while blue colors indicate smaller SOC stocks by the emulator compared to GSDE.

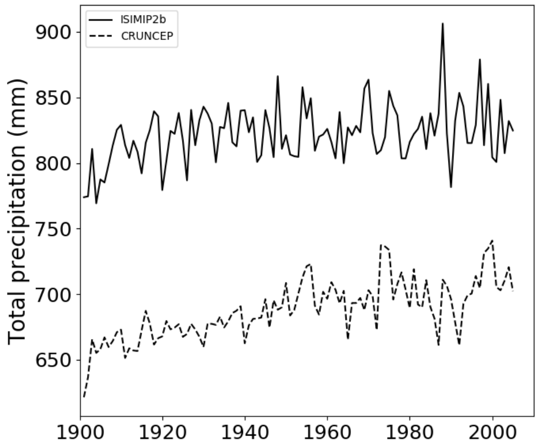

Figure S2: Temporal trend in yearly total, global average precipitation derived from ISIMIP2b (staright line) and CRU-NCEP (dashed line).